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HTS PARTIAL CORE TRANSFORMER-FAULT CURRENT LIMITER

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1. Introduction

In 1908, a Dutch physicist Kamerlingh Onnes, was the first person to liquefy helium at 4.2 K. Subsequently in 1911, he was able to discover that mercury, when cooled by liquid helium, has no electrical resistance. He named this phenomenon "Superconductivity". Although superconductors were discovered in 1911, high temperature superconductors (HTS) were only discovered in 1987. This enabled material to become superconducting at liquid nitrogen temperature[1]. As a result, the operating cost of using superconductors came down. This opened the way to use superconductors in power system applications[2].

The basic premise behind using superconductors is that they tend to quench once the magnetic field density, temperature and conductor current are breached beyond their combined critical limit. Once this limit is breached, they tend to change from a superconducting state to a resistive state. It is this behaviour of superconductors that has carved the path towards using superconductors as fault current limiters.

This paper presents a HTS partial core transformer-fault current limiter that was designed and built at the University of Canterbury. The transformer was tested under no load, short circuit and full load conditions, followed by a test with a short circuit fault to determine its capability as a fault current limiter.

2. Device description and design method

The device has a structure which is both a partial core transformer and a fault current limiter. A partial core transformer is a transformer with its yokes and limbs removed [3]. This makes the transformer light weight, and construction and transportation is much easier. The tradeoff of this design is that it increases the magnetizing current of the transformer due to the higher reluctance of the magnetic circuit. The higher magnetizing current results in higher copper losses and therefore a larger cross-sectional area is required for the windings. Hence, a conductor which has very low losses and a small cross-sectional area is required. This brings the HTS into the picture which has all the above required characteristics. In addition, HTS has the advantage of quenching which makes it useful for current limiting.

The reverse design method is used to design this device [3]. The method takes into account the physical characteristics such as material resistivities, permeabilites and the dimensions of the windings and the core as the specifications. By altering these specifications, the performance of the device is optimized and a suitable design is obtained.

An Excel program has been developed for simulation purposes and this serves as a gauge to test the proposed design before actually fabricating it. The key parameters considered while designing the transformer are listed in Table 1. Modifications are made to allow for the new combined device of a transformer-fault current limiter. A Steinmetz model, shown in Fig. 1, is used to depict the equivalent circuit parameters of the combined device [3].

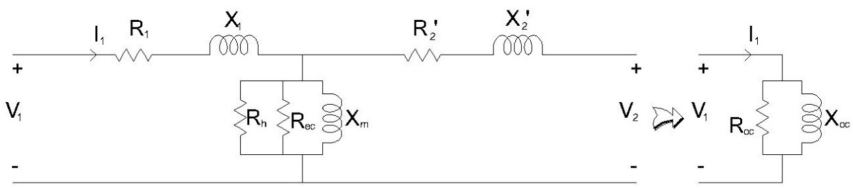

Fig 1. Steinmetz model of a transformer-fault current limiter

In the above circuit diagram the inside winding resistance and reactance are R_1 and X_1 respectively, while the outside winding resistance and reactance, referred to the inside winding, are $R_2^{'}$ and $X_2^{'}$ respectively. R_h, R_{ec} and X_m represent the core hysteresis losses, eddy current losses and magnetising current respectively.

2.1 Core

The core was constructed from high permeability, grain oriented silicon steel. It was designed as a circular core with stacked laminations arranged in parallel. The dimensions of the core are listed in Table 1.

Parameter	Dimension
Core length	384mm
Diameter of core	80mm
Stacking factor	0.86
Lamination thickness	0.23mm
Operating temperature	-50^0C
Former thickness	19.5 mm
Material density	7700kg/m^3

Table 1. Design data of the partial core

2.2 Windings

The HTS windings were wound on a former made of G10 composite, as shown in Figure 2. The composite was fabricated by an outside vendor. The emphasis on choosing G10 composite was its ability to withstand liquid nitrogen and an operating temperature of 77K. In order to prevent inter-turn short circuits, the HTS windings are insulated with Nomex tape. Spacers were used between each layer to accommodate cooling of the windings. This allowed liquid nitrogen to freely flow between the windings on each layer. Figure 3 shows the top view of the windings in AutoCAD. In this figure, the white spacers are shown to wrap around the former. This allows for the 2mm spacing in between each winding. The primary/inside winding consisted of 6 layers while the secondary/outside winding consisted of 6.5 layers. The specifications for the windings are given in Table 2.

This model design was achieved using the reverse design method over several iterations. Appropriate efficiency, regulation and the fault current level were taken into account while performing these iterations. The 6.5 layers in the secondary were wound in a circular pattern with the last half layer wound on the centre. This ensured symmetrical flux distribution along the device. Figure 4 displays the fabricated device with the windings wound on the former.

Parameter	Inside Winding	Outside Winding
Winding height	384mm	384mm
Number of layers	6	6.5
Turns per layer	73	73
Conductor length	189m	267m
Wire width	4.1mm	4.1mm
Wire thickness	0.3mm	0.3mm
Wire insulation thickness	5.5mm	5.5mm
Insulation layer space	2 mm	2 mm
Operating temperature	77K	77K

Table 2. Winding data of the transformer-fault current limiter

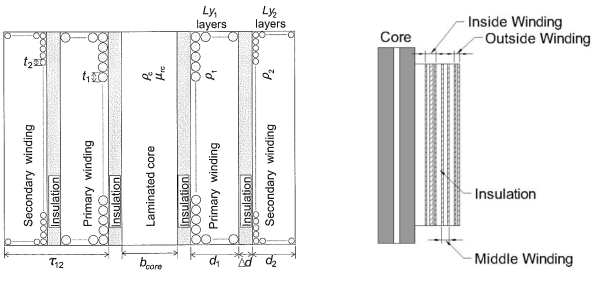

Fig 2. Axial representation of the partial core transformer-FCL

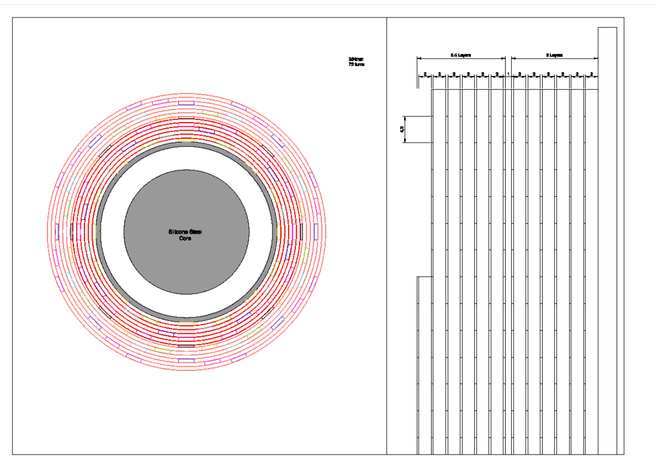

Fig 3. AutoCAD representation of the windings from Top view

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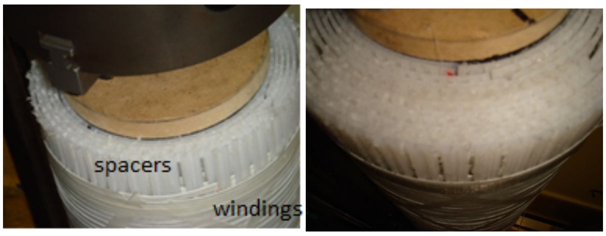

Fig 4. HTS windings wound around the former with spacers in between

2.3 Cryogenic equipment for cooling

To maintain the transformer under cryogenic conditions, a vacuum Dewar, shown in Fig. 5 was filled with liquid nitrogen (LN2). The vacuum Dewar consists of an inner vessel for storing the LN2 and an outer vessel exposed to room temperature with a vacuum between them. The vacuum is present to limit convection losses to the LN2 from the outside. To limit radiation losses, several layers of aluminized non-stretch polyester were wrapped around the inner vessel. Care was taken not to create shorted turns by insulating the aluminized non-stretch polyester with vacuum rated tissue paper. The bottom of the inner vessel was dome shaped so that the joint between the dome and the tube of the inner vessel, when exposed to LN2, expanded and contracted evenly. A pressure relief port is present on the outside of the Dewar in case a failure of the inner vessel results in nitrogen gas venting into the vacuum chamber.

The core vessel is similar to the vacuum Dewar in that a vacuum is formed between the core and the LN2. A similar arrangement of aluminized polyester and tissue was used in the core vessel. The HTS winding former is fitted over the core vessel and held in place with a clamping ring. A float is attached to the core vessel to indicate the minimum and maximum LN2 levels. A filling tube for the LN2 is also fitted to the outside of the core vessel. A pressure relief port is present on the top of the core vessel in case a failure vents nitrogen gas into the vacuum chamber.

Fig 5. Cryogenic equipment for HTS transformer-fault current limiter

3. Testing

Electrical tests were performed on the combined unit of the transformer-fault current limiter to determine its operational characteristics. The HTS transformer-fault current limiter was operated under no-load, short circuit, full load and fault conditions, and then subjected to an endurance run.

3.1 Experimental Setup

3.1.1 Preview of the lab

The tests are performed in the High Voltage Lab of the University of Canterbury. The facility is equipped with a single phase power supply that can deliver 600A at 400V. Its large size helps to accommodate the test equipment and the device with adequate spacing between them.

3.1.2 Test Gear

The test gear used in this experimental setup consisted of two calibrated Fluke 41B meters for measuring voltage, current and power of the primary and secondary windings. The meters were connected to a computer through an IEEE-488 interface which ran a Matlab program to collect the data recorded from the tests. For measuring the resistance of the windings under dc conditions, a MPK254 digital micro-ohmmeter was used. The insulation tests were performed with a Megger meter with model specs S1-5005.

For energising the transformer-fault current limiter, two transformer variacs were used. They were connected in series. The first variac was the laboratory's 600 A supply, while the second variac was the 70 A supply. The 70 A variac is portable and allows for adjusting the voltage in steps while recording and monitoring the measurements. The experimental setup is shown in Fig.6

Fig 6. Experimental setup of the HTS transformer-fault current limiter

3.2 Open circuit test

With an open circuit or no load test, very little current is required to energise the core. Since the secondary is open circuited, all the current flows through the primary winding and the losses are attributed as the core losses. The open circuit test also determines the voltage ratio of the primary and the secondary windings.

To perform the test, the voltage in the second variac is increased in small increments to the rated voltage and the measurements are recorded. The measured results are given in Table 3. They are compared to the calculated results determined from the design program. There is generally good agreement between the measured and calculated results.

Parameter	Measured	Calculated
Inside winding voltage (V)	230.6	230
Outside winding voltage (V)	235	237
Voltage ratio	1.02	1.03
Excitation current (A)	13.6	15.4
Excitation current's phase	-87	-86
Volt-amperes (kVA)	3.14	3.54
Real power (W)	167	165
Power factor	0.05	0.05

Table 3: Open circuit test results

3.3 Short circuit test

In a short circuit test, the secondary is shorted. The test determines the series impedance and full load losses in the combined unit. All the losses are related to the windings. The results from the short circuit test are given in Table 4. Again there is good agreement between the measured and calculated results.

Parameter	Measured	Calculated
Inside winding voltage (V)	42.1	42.3
Inside winging current (A)	30.1	31.3
Outside winding current (A)	26	28
Volt-amperes (kVA)	12.6	13.0
Real Power (W)	47	50
Power factor	0.03	0.04
Inside winding current's phase in deg	-88	-87

Table 4: Short circuit test results

3.4 Load test

The load test on the HTS transformer-fault current limiter determines the performance of the device while delivering power. The device was connected to a resistive load bank as illustrated in Fig 7. The supply voltage was varied on the primary side till it reached the rated voltage and the load resistance varied till it reached the rated value. The results from this test are given in Table 5. Again there is good correlation between the measured and calculated values.

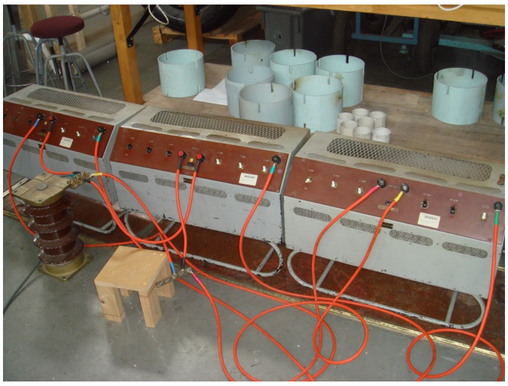

Fig 7. Load bank to perform the load test

Parameter	Measured	Calculated
Inside winding voltage (V)	**230**	**230**
Inside winding current (A)	**33**	**31.3**
Outside winding voltage (V)	**234.5**	**234.5**
Outside winding current (A)	**30.7**	**24.2**
Outside winding current's phase (deg)	**-34**	**-32**
Volt-amperes (VA)	**7.2**	**7.2**
Real power (kW)	**6.8**	**5.7**
Power factor	**0.84**	**0.80**
Efficiency (%)	**99.97**	**99.96**
Voltage Regulation (%)	**5.7**	**5.8**

Table 5: Load test results

3.5 Fault current test

The transformer and fault current limiter was tested under a fault condition. The test was performed by shorting the secondary windings with a manual switch while the primary winding was energised with the rated voltage and the rated load was connected to the secondary side of the transformer. Fig 8 depicts the arrangement of the rated load and the manual switch used in this test to short the secondary windings. The voltage and current for the primary and secondary windings were monitored using an oscilloscope. The images obtained are shown in Fig 9. In the channel traces, the green waveform indicates the primary current while the yellow waveform indicates the secondary current. Each square block in the oscilloscope chart has amplitude of 100A for the current. The measured fault current after quenching was 200A as compared to the calculated prospective current of 173A determined using the reverse design model. The circuit being inductive means that the voltage leads the current as show in the second image of Fig 9.

Fig 8. Fault current test

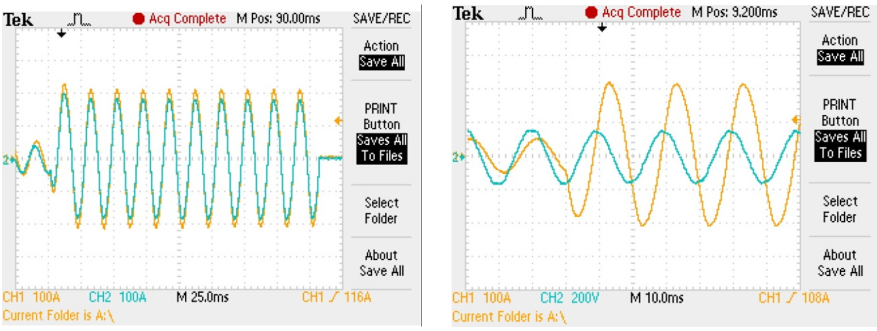

Fig 9. Oscilloscope images of the primary voltage, (V) and current, (A) during a fault condition.

Under normal conditions, the HTS acts as a conductor with almost zero resistance, however, once the critical current, I_c of the HTS material (BSCCO) has been breached, it quenches and turns resistive. The fault limiting capabilities of the HTS material was modelled by taking into account the resistive properties of silver.

4. Conclusion

This paper begins with a brief about superconductors and how they were applied in power system applications. It highlights the advantages of a partial core design as a transformer and its application in the combined device of transformer-fault current limiter. The fabricated design is then displayed followed by the results of tests done to investigate its feasibility as a current limiter. The measured values from the test and the reverse design model are found to have close correlation which confirms that the model can be used to design current limiters and transformers.

5. References

1. At the Frontiers of Science: Superconductivity and its Power Applications. NREL, July 1998.

2. Keisuke Fushiki, Tanzo Nitta, Jumpei Baba et al., “Design and Basic Test of SFCL of Transformer Type by Use of Ag Sheathed BSCCO wire,” Applied Superconductivity, vol17, no2, June 2007.

3. Liew, M.C. and Bodger, P.S., "Applying a reverse design modelling technique to partial core transformers", AUPEC2001, Perth, Australia, 23-26 September, 2001, paper 020, pp. 310-315.